

Saving fourth generation and baryon number by living long

Hitoshi Murayama ^{a,b,c}, Vikram Renteria ^{d,e}, Jing Shu ^b, and Tsutomu T. Yanagida ^b

^a *Department of Physics, University of California, Berkeley, CA 94720.*

^b *Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Japan 277-8568*

^c *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

^d *Department of Physics, University of Arizona, Tucson, AZ 85721*

^e *Department of Physics, University of California, Irvine, CA 92697.*

Recent studies of precision electroweak observables have led to the conclusion that a fourth generation is highly constrained. However, we point out that a long-lived fourth generation can reopen a large portion of the parameter space. In addition, it preserves baryon and lepton asymmetries against sphaleron erasure even if $B - L = 0$. It opens up the possibility of exact $B - L$ symmetry and hence Dirac neutrinos. The fourth generation can be observed at the LHC with unique signatures of long-lived particles in the near future.

When the muon was discovered as an exact copy of the electron but with a higher mass, people wondered why nature repeats in an apparently unnecessary fashion. Later, discovery of CP violation led Kobayashi and Maskawa to predict that nature actually repeats itself *at least* three times. There is no obvious reason why it should stop with three. At the same time, CP violation also led Sakharov to consider how the apparent lack of anti-matter in the universe might be explained. Therefore the apparent repetition of generations of elementary particles has an intimate connection with the issue of baryogenesis.

The fourth generation (4G) is indeed the simplest extension of the standard model being searched for at Tevatron and at the LHC. However, several groups have claimed recently that this simple extension of the standard model (SM) is highly constrained [1–3] or already ruled out with no (CKM) mixing to the SM [4] by a combination of collider searches for its direct production and its indirect effects in Higgs boson production, together with the precision electroweak observables.

In this letter, we consider a long-lived 4G due to extremely small mixings between the fourth and lighter three generations. It could be a consequence of a flavor symmetry or compositeness of the 4G. We then point out that such a 4G evades these constraints. This is because the 4G neutrino can be nearly stable, and it can be below the nominal LEP-II limit. Its loops can generate negative S , which in turn allows for a heavier Higgs boson, and positive T for a small splitting between 4G up- and down-type quarks.

Interestingly, such a long-lived 4G has an important implication for baryogenesis. The baryon number B is usually believed to be erased unless there is a non-vanishing asymmetry in $B - L$. However, the longevity of the 4G provides additional conserved numbers beyond $B - L$, which in turn protects B from erasure. Therefore, the longevity leads to both 4G asymmetry and B asymmetry. It even allows for an exact $B - L$ symmetry of nature, either global or local, making us reconsider the origin of neutrino mass and baryon asymmetry.

Let us first discuss the current constraints on the 4G particles, with the obvious notation U , D , E , and N . The electroweak precision tests (EWPTs) for the chiral 4G are summarized in Ref. [5] with some more recent updates in Ref. [1, 3]. Here we use the latest global fit results from Ref. [1] which

include the constraints from the low-energy data. The S - T ellipse in [1] looks somewhat more horizontal (large positive T is not preferred now) than the one used in Ref. [5] from the LEP Electroweak Working Group [6]. As a consequence, some of the sample points in Ref. [5] do not lie in the 95% C.L. in the S - T plot and the allowed parameter space for m_U, m_D is much smaller.

If the 4G Dirac neutrino decays, it has to be heavier than 90.3 GeV [7]. However if it is long lived at LEP, then the only bound is $m_N > 45.0$ GeV from the invisible Z decay width. For the charged leptons, the bound is $m_E > 102.6$ GeV for the long-lived case and $m_E > 100.8$ GeV for the shorted-lived case [7]. Unlike all the previous papers, which assumed $m_{E,N} \gtrsim 100$ GeV, we scan over all possible 4G lepton masses. All the S , T contributions from 4G fermions are calculated from the exact one-loop formulae in Ref. [8] while the two-loop Higgs contribution is obtained from fitting the previous results. The Higgs mass is chosen within the two allowed mass regions, $m_h = 130 < 131$ GeV (light) and $m_h = 300 > 204$ GeV (heavy) at 95% C.L. from the latest Higgs boson search at the Tevatron [9] that includes the loop of the 4G in the gluon-fusion process.

There are also lower bounds from direct searches for the fourth-generation quarks at the Tevatron. In the long-lived case, we infer the bounds from the limit on stable stop [10]. Rescaling the production cross section with the $U\bar{U}$ production rate at NLO level [11] gives us $m_D \geq m_U > 340$ GeV and $m_U \geq m_D > 310$ GeV at 95% C. L. For the short-lived case, we obtain $m_U > 335$ GeV from W +jets [11] if $m_D \geq m_U$ and $m_D > 338$ GeV if $m_U \geq m_D$ and D decays dominantly into $W + t$ [12]. The bound does not change significantly for a sizable branching ratio $D \rightarrow W$ +jets [13].

There are also upper bounds for the $Q = U$ or D mass from tree level unitarity. The most stringent bounds are from the scattering $Q\bar{Q} \rightarrow Q\bar{Q}$ which includes the color off-diagonal amplitudes [14]. Requiring the eigenvalue of the tree-level partial-wave amplitude to be smaller than 1/2, we find

$$\frac{2\sqrt{2}\pi}{G_F} > [3(m_U^2 + m_D^2) + \sqrt{9(m_U^2 - m_D^2)^2 + 16m_U^2 m_D^2}]. \quad (1)$$

Regarding the unitarity limit, remember that the amplitude is

only calculated at the tree level and hence the bound is soft.

The allowed mass region for the fourth-generation quarks is presented in Fig. 1. Firstly and most importantly, we find a large allowed region for $m_U \lesssim m_D$ as opposed to previous analyses which assumed $m_{E,N} \gtrsim 100$ GeV, whose contribution to the S parameter is positive together with the Higgs contribution. Then the S -parameter constraint only allows a small mass region for $m_U > m_D$. However, for a light fourth-generation neutrino (around 46 GeV), the fourth-generation lepton contribution to the S parameter is negative (around -0.09). Hence, large fourth-generation quark masses ($m_U \lesssim m_D$) with a relatively large S parameter are allowed. Secondly, varying m_h does *not* change the allowed parameter space because decreasing m_N can compensate for the S , T contribution from increasing the Higgs mass.

In Ref. [4], it is claimed that the 4G with small mixing is ruled out by the a combination of EWPTs, direct searches and the indirect bounds from the Higgs production at Tevatron. We will explain our disagreement with the author. The author first fixes $m_U - m_D = 16$ GeV and $m_E - m_N = 91$ GeV [1] which is a very limited region of the allowed parameter space which is clear from our Fig. 1. Then he finds the Higgs mass required by EWPTs in the zero mixing case for the two end point mass of m_U and m_D in the line $m_U - m_D = 16$ GeV is ruled out by the direct Tevatron Higgs boson search. However, the mixing between 3rd and 4th generation increases the T parameter only (see formula one in Ref. [4]), effectively the same as increasing the U and D mass splitting [29].

Having demonstrated that longevity makes the 4G phenomenologically viable, we now turn our attention to the baryon asymmetry. In the SM, B and L are separately conserved except for the sphaleron transitions [15] which violate $B + L$ but preserve $B - L$. The net B must be proportional to the only conserved quantity $B - L$ and would be zero if $B - L = 0$. After the sphaleron transitions get decoupled from thermal equilibrium at T_{sph} , B is a conserved quantity which gives us the right number density today.

If the 4G fermions do not mix with the lighter generations significantly, they would stay in chemical equilibrium only through the electroweak sphaleron transitions, which maximally violate $3B + 3L + B_4 + L_4$ instead. Here we use B or L as the baryon or lepton number in the first three generations. In this case, the other three orthogonal combinations of B , L , B_4 , L_4 are conserved charges. The final B is a linear combination of these conserved charges instead of just being proportional to $B - L$. As a consequence, unless there exists some accidental cancellations, the net baryon number density would be nonzero even if $B - L = 0$.

The thermal history for baryon number generation after inflation is summarized as follows. First, we assume there is some baryogenesis mechanism which generates a net baryon asymmetry $B + B_4 = L + L_4 \neq 0$. However, this initial condition could generate an asymmetry in the other conserved charges (for instance, $L - 3L_4$). Above the critical temperature T_c of the electroweak phase transition, all particles are massless and net B could be small or zero depending on the

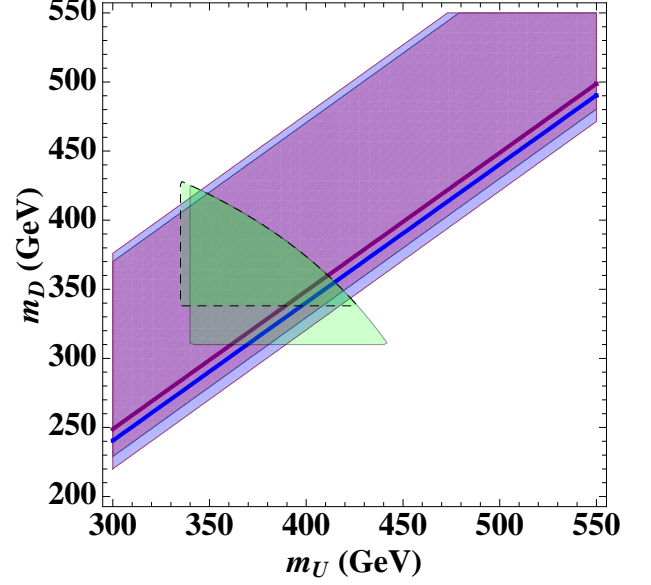


FIG. 1: The m_D vs m_U contour plot for varying fourth-generation lepton masses. The purple region is the allowed mass region from the S - T constraint at 95% C.L. for $m_h = 130$ GeV and the blue region (including the purple region) is that for $m_h = 300$ GeV. The lower limit of the green region comes from the direct searches at the Tevatron (The solid line is the case for long-lived fourth-generation quarks and the dashed line is the case for the prompt decay), while the upper limit is the bound from unitarity. The purple and the blue lines use the approximate formula for the fourth generation quark masses $m_U - m_D = (1 + \frac{1}{5} \log(\frac{m_h}{115 \text{ GeV}})) * 50$ GeV from Ref. [5] for $m_h = 130$ GeV and 300 GeV, respectively.

particle content of the model. Below T_c , all fermions gain their masses via the Higgs mechanism, so it costs additional energy to create the heavy fourth generation fermions. Once the temperature drops below their masses, the mass effect essentially blocks the sphaleron process from erasing B [30].

We follow the standard analysis in Ref. [16] while taking into account all the mass effects. We choose a single chemical potential μ_l for leptons instead of separate chemical potentials for each light lepton flavor as in Refs. [17–20]. We consider the SM matter consisting of three families, each of which consists of two quarks (an up-type and down-type) with masses m_{q_i} , a charged lepton of mass m_{l_i} and a massless neutrino. The SM interactions relate all the chemical potentials which leave us with six independent chemical potentials in our case: $\mu_{u_L}, \mu_{u_R}, \mu_{d_L}, \mu_{d_R}, \mu_{e_L}, \mu_{e_R}$ which are the chemical potentials for upper type quarks, W^- bosons, neutral Higgs boson, 4G up type quark, 4G neutrino, sum over all SM neutrino chemical potentials.

$$\begin{aligned}
 \mu_{d_L} &= \mu_{u_L} + \mu_W & (W^- \leftrightarrow \bar{u}_L + d_L) \\
 \mu_{D_L} &= \mu_{U_L} + \mu_W & (W^- \leftrightarrow \bar{U}_L + D_L) \\
 \mu_{e_L} &= \mu_{\nu_L} + \mu_W & (W^- \leftrightarrow \bar{\nu}_L + e_L) \\
 \mu_{E_L} &= \mu_{N_L} + \mu_W & (W^- \leftrightarrow \bar{N}_L + E_L) \\
 \mu_{u_R} &= \mu_0 + \mu_{u_L} & (\phi^0 \leftrightarrow \bar{u}_L + u_R)
 \end{aligned}$$

$$\begin{aligned}
\mu_{U_R} &= \mu_0 + \mu_{U_L} & (\phi^0 \leftrightarrow \bar{U}_L + U_R) \\
\mu_{d_R} &= -\mu_0 + \mu_W + \mu_{u_L} & (\phi^0 \leftrightarrow \bar{d}_L + \bar{d}_R) \\
\mu_{D_R} &= -\mu_0 + \mu_W + \mu_{U_L} & (\phi^0 \leftrightarrow \bar{D}_L + \bar{D}_R) \\
\mu_{e_R} &= -\mu_0 + \mu_W + \mu_i & (\phi^0 \leftrightarrow e_L + \bar{e}_R) \\
\mu_{E_R} &= -\mu_0 + \mu_W + \mu_{N_L} & (\phi^0 \leftrightarrow E_L + \bar{E}_R) \\
\mu_{N_R} &= -\mu_0 + \mu_W + \mu_{N_L} & (\phi^0 \leftrightarrow N_L + \bar{N}_R)
\end{aligned} \quad (2)$$

The mass correction to the particle number asymmetry density n_p is

$$\begin{aligned}
n_p &= \frac{g_p T^3}{\pi^2} \left(\frac{\mu}{T} \right) \int_x^\infty y \sqrt{y^2 - x^2} \frac{e^y}{(1 \pm e^y)^2} dy \\
&= \begin{cases} \frac{g_p T^3}{3} \left(\frac{\mu}{T} \right) \alpha_b(x) & p \text{ is a boson,} \\ \frac{g_p T^3}{6} \left(\frac{\mu}{T} \right) \alpha_f(x) & p \text{ is a fermion,} \end{cases} \quad (3)
\end{aligned}$$

where we assume $n_p \propto \mu$ for small asymmetries. g_p is the number of internal degrees of freedom and $x = m/T$. The mass correction functions for bosons and fermions are normalized as $\alpha_b(0) = \alpha_f(0) = 1$. We define $\Delta \equiv N - \sum_i \alpha_i$ ($N = 3$) for SM particles with $i = 1, 2, 3$ generations. Δ_u , Δ_d and Δ_i stands for the overall mass corrections for up type SM quarks, down type SM quarks and SM charged leptons, respectively. The α_W , α_0 , α_U , α_D , α_E and α_N are the mass function in Eq. (3) for W boson, neutral Higgs, 4G up-quark, 4G-down quark, 4G charged lepton and 4G neutrino respectively. It is easy to see Δ_d and $\Delta_i < 5 \times 10^{-4}$ since $T_{\text{sph}} > m_W$ so we will ignore their contribution in the following discussions. The neutral Higgs boson condenses so we have $\mu_0 = 0$. One can write the charge densities in terms of the chemical potential (upto irrelevant constants):

$$\begin{aligned}
Q &\approx 2(N - 2\Delta_u)\mu_{u_L} - 2(2N + 3\alpha_W)\mu_W - 2\mu \\
&\quad + 4\alpha_U\mu_{U_L} - 2\alpha_D(\mu_{U_L} + \mu_W) - 2\alpha_E(\mu_{N_L} + \mu_W) \\
B &\approx (4N - 2\Delta_u)\mu_{u_L} + 2N\mu_W \\
L &\approx 3\mu + 2N\mu_W \\
B_4 &= 2\alpha_U\mu_{U_L} + 2\alpha_D(\mu_{U_L} + \mu_W) \\
L_4 &= 2\alpha_N\mu_{N_L} + 2\alpha_E(\mu_{N_L} + \mu_W), \quad (4)
\end{aligned}$$

where the net Q (electric charge density) must be 0. The conserved charge densities are

$$\begin{aligned}
B - L &= (4N - 2\Delta_u)\mu_{u_L} - 3\mu \\
B_4 - L_4 &= 2\alpha_U\mu_{U_L} + 2\alpha_D(\mu_{U_L} + \mu_W) \\
&\quad - 2\alpha_N\mu_{N_L} - 2\alpha_E(\mu_{N_L} + \mu_W) \\
L - 3L_4 &= 3\mu + 2N\mu_W - 6\alpha_N\mu_{N_L} \\
&\quad - 6\alpha_E(\mu_{N_L} + \mu_W). \quad (5)
\end{aligned}$$

The electroweak sphaleron process which converts $qqql$ of each generation into nothing give us the last constraint

$$3N\mu_{u_L} + 2(N+1)\mu_W + \mu + 3\mu_{U_L} + \mu_{N_L} = 0. \quad (6)$$

Now we can pick up two sample spectra which are consistent with the most recent data, $m_N = 46$ GeV, $m_E = 103$

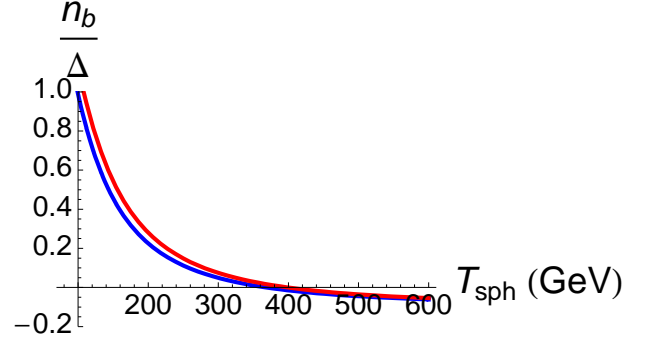


FIG. 2: The final baryon asymmetry versus the initial asymmetry n_b/Δ as a function of sphaleron freeze-out temperature T_{sph} (GeV). The blue (red) lines are for $m_N = 46(46)$ GeV, $m_E = 134(103)$ GeV, $m_U = 350(380)$ GeV, $m_D = 350(380)$ GeV, $m_{\phi_0} = 300(130)$ GeV.

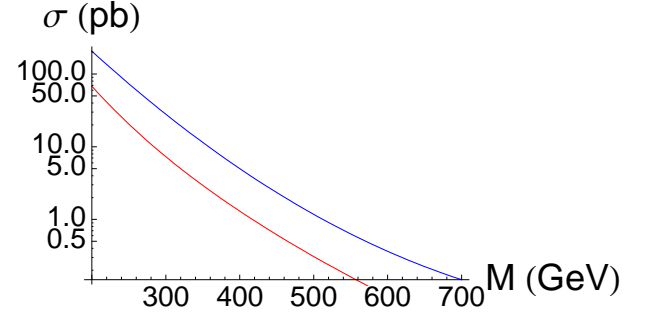


FIG. 3: Production rate for the $U\bar{U}$ at the LHC, the blue curve is the cross section $\sigma(pp \rightarrow U\bar{U})$ computed by PYTHIA at the LHC with $\sqrt{s} = 14$ TeV from Ref. [23]. The red curve is the one at the early LHC with $\sqrt{s} = 7$ TeV at the NLO level from [24, 25].

GeV, $m_U = 380$ GeV, $m_D = 380$ GeV, $m_{\phi_0} = 130$ GeV or $m_N = 46$ GeV, $m_E = 134$ GeV, $m_U = 350$ GeV, $m_D = 359$ GeV, $m_{\phi_0} = 300$ GeV and show how the final baryon asymmetry is obtained from an initial baryon asymmetry with $B - L = 0$. The full numerical results including all the mass effects are presented in FIG. 2. We choose the initial asymmetry as $B = L = 3\Delta$, $B_4 = L_4 = 0$ and use the minimal 4G, $m_t = 172$ GeV, $m_W = 80$ GeV. One can clearly see that the final baryon number density is the same order as the initial baryon number density 3Δ if the sphaleron decoupling temperature is not too high. Note that even for very high sphaleron decoupling temperature T_{sph} when the 4G fermions are essentially massless, the baryon number is not completely erased because of the mismatch in the number of the neutrino degrees of freedom.

For the LHC signals of the long-lived 4G quarks [31], we first estimate their proper lifetime. U/D have to decouple from the SM fermions above the sphaleron freeze-out temperature T_{sph} which gives us the lower limit on the proper lifetime: $\Gamma(U/D \rightarrow qW^\pm) < H \sim T_{\text{sph}}^2/M_{\text{pl}}$. The long-lived particles U/D should not disrupt the success of BBN which gives us the upper limit of the proper lifetime. Then

the allowed window for the proper lifetime is $10^{-10}\text{s} < \tau_Q < 1\text{s}$, which also corresponds to the small mixing angle $10^{-13} < \theta < 10^{-8}$. Their decay length at the LHC is $d = \beta c \tau \gamma \approx (30\text{mm}) (\tau/10^{-10}\text{s}) \beta \gamma$. If the lifetime is relatively short within the above range, the 4G quarks show displaced vertices in their decays. On the other hand, if the 4G quarks decay outside the detector, the lighter 4G quark would hadronize and the signal would look like a jet with tracks, with anomalously large energy deposits in the silicon detector or delayed hits in the calorimeters or muon chamber. At the early LHC, this is one of the signals that can be looked for. At the same time, it may cause confusion if the charge-exchange reaction with the detector material causes the charged bound state to turn neutral and vice versa, making the track a “dashed line” [28].

Unfortunately, we are not aware of any ATLAS/CMS simulation on the long-lived 4G quarks. However, we can rescale the production rate and use the study for the long-lived stop since the spin effect is negligible for mesons or baryons with a heavy constituent. The production rate for stop at the 14 TeV LHC and 4G U at $\sqrt{s} = 7\text{ TeV}$ is presented in Fig. 3. We can see that for a typical mass range ($300 \sim 400\text{ GeV}$) allowed by EWPTs, direct searches and unitarity limit, the 4G U production rate at $\sqrt{s} = 7\text{ TeV}$ LHC is roughly 1/8th of stop production rate at $\sqrt{s} = 14\text{ TeV}$ LHC. In Table I, we list the several required integrated luminosity \mathcal{L}_{int} for LHC at $\sqrt{s} = 14\text{ TeV}$ to observe 3 events in CMS [26] for the long-lived stop production of different masses. If we assume that the acceptance for the signals to pass the cuts and the background are similar in the above two situations, we can estimate the order of magnitude for the required integrated luminosities to observe hints (*e.g.*, about three events) at the LHC ($\sqrt{s} = 7\text{ TeV}$) is $\mathcal{L}_{\text{int}} = 10 \sim 10^2\text{ pb}^{-1}$ which is promising for the end of this year. With more data accumulated at the $\mathcal{L}_{\text{int}} \simeq 1\text{ fb}^{-1}$, we expected that there would be decisive evidence for such unique signatures of long-lived particles.

We would like to thank Qinghong Cao for providing the production rate at the NLO level for light 4th generation quark at the early LHC. The work is partially supported by the World Premier International Research Center Initiative (WPI initiative) MEXT, Japan. H.M. was also supported in part by the U.S. DOE under Contract DE-AC03-76SF00098, in part by the NSF under grant PHY-04-57315, and in part by the Grant-in-Aid for scientific research (C) 20540257 from Japan Society for Promotion of Science (JSPS). J.S. is also supported by the Grant-in-Aid for scientific research (Young Scientists (B) 21740169) from JSPS.

TABLE I: The required integrated luminosity \mathcal{L}_{int} for LHC $\sqrt{s} = 14\text{ TeV}$ to observe 3 events for the long-lived stop production for their different masses. The data are quoted from Fig. 2 (left) in Ref. [26].

$\mathcal{L}_{\text{int}} (\text{pb}^{-1})$	0.2	1	4	20	40	100
$m (\text{GeV})$	200	300	400	500	600	700

- [1] J. Erler and P. Langacker, Phys. Rev. Lett. **105**, 031801 (2010).
- [2] S. Dawson and P. Jaiswal, arXiv:1009.1099 [hep-ph].
- [3] O. Eberhardt, A. Lenz and J. Rohrwild, arXiv:1005.3505 [hep-ph].
- [4] M. S. Chanowitz, arXiv:1007.0043 [hep-ph].
- [5] G. D. Kribs, *et al*, Phys. Rev. D **76**, 075016 (2007).
- [6] <http://www.cern.ch/LEPEWWG/plots/summer2006>
- [7] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).
- [8] H. J. He, N. Polonsky and S. f. Su, Phys. Rev. D **64**, 053004 (2001).
- [9] T. Aaltonen *et al.* [CDF Collaboration and D0 Collaboration], arXiv:1005.3216 [hep-ex].
- [10] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 021802 (2009).
- [11] http://www-cdf.fnal.gov/physics/new/top/2010/tprop/Tprime_v46_public/public.4.6.html
- [12] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **104**, 091801 (2010).
- [13] C. J. Flacco, D. Whiteson, T. M. P. Tait and S. Bar-Shalom, arXiv:1005.1077 [hep-ph].
- [14] M. S. Chanowitz, M. A. Furman and I. Hinchliffe, Nucl. Phys. B **153**, 402 (1979).
- [15] F. R. Klinkhamer and N. S. Manton, Phys. Rev. D **30**, 2212 (1984), P. B. Arnold and L. D. McLerran, Phys. Rev. D **37**, 1020 (1988).
- [16] J. A. Harvey and M. S. Turner, Phys. Rev. D **42**, 3344 (1990).
- [17] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B **191**, 171 (1987).
- [18] H. K. Dreiner and G. G. Ross, Nucl. Phys. B **410**, 188 (1993).
- [19] J. Shu, T. M. P. Tait and C. E. M. Wagner, Phys. Rev. D **75**, 063510 (2007).
- [20] S. M. Carroll and J. Shu, Phys. Rev. D **73**, 103515 (2006).
- [21] R. M. Godbole, S. K. Vempati and A. Wingerter, JHEP **1003**, 023 (2010).
- [22] S. M. Barr, R. S. Chivukula and E. Farhi, Phys. Lett. B **241**, 387 (1990); M. R. Buckley and L. Randall, arXiv:1009.0270 [hep-ph].
- [23] L. Quertenmont [ATLAS Collaboration and CMS Collaboration], *Prepared for 16th International Workshop on Deep Inelastic Scattering and Related Subjects (DIS 2008), London, England, 7-11 Apr 2008.*
- [24] E. L. Berger and Q. H. Cao, Phys. Rev. D **81**, 035006 (2010).
- [25] Q. H. Cao, private communication.
- [26] A. Rizzi, AIP Conf. Proc. **1200**, 758 (2010).
- [27] K. Dick, *et al* Phys. Rev. Lett. **84**, 4039 (2000); H. Murayama and A. Pierce, *ibid*, **89**, 271601 (2002).
- [28] M. Fairbairn, A. C. Kraan, D. A. Milstead, T. Sjostrand, P. Z. Skands and T. Sloan, Phys. Rept. **438**, 1 (2007).
- [29] The Yukawa couplings hit the Landau pole below 100 TeV or so. We will not discuss its UV completion above this energy scale as it is irrelevant to the following discussions.
- [30] There are related scenarios which generates the dark matter abundance through sphalerons [22], preserves B relying on τ lepton mass [19] or Dirac neutrino mass [27].
- [31] The estimation of the proper lifetime and traveling distance also applies to the forth generation quarks, and the lightest fourth generation neutrino will look like missing energy.